n+p $\rightarrow$ d + γ ;
A measurement of the weak force between protons and neutrons

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The n+p$\rightarrow$d+γ experiment measures the parity-violating directional gamma-ray asymmetry, A_γ, with uncertainties of $0.5\text{x}10^{-8}$ when cold polarized neutrons are captured by para-hydrogen. This precision measurement will determine the long-range pion-nucleon weak coupling constant, H_π^1, with a precision of 10% of its predicted value, and thus will help to clarify our understanding of the weak interaction between nucleons. The n+p$\rightarrow$d+γ experiment on the SNS beamline 14B is designed to take advantage of the high intensity of the source and its pulsed nature. The experiment requires a 30-Hz pulsed beam for optimal performance. In three months of run time the experiment will achieve a statistical uncertainty of $0.5\text{x}10^{-8}$.

The high-intensity Spallation Neutron Source (SNS) opens new and exciting possibilities to perform fundamental physics experiments with polarized pulsed cold neutrons. These new types of precision experiments can be designed to take full advantage of the knowledge of the neutron energy through use of time-of-flight information.

The parity-violating (PV) ΔI=1 pion-nucleon coupling constant H_π^1 gives the strength of the longest-range part of the PV nucleon-nucleon force [1]. A number of hadronic PV experiments have tried to determine the value of H_π^1. Significant results have been obtained from five measurements of circular polarization, P_γ of photons in the decay of ^{18}F [2]. The combined result gives an upper limit for H_π^1 that is considerably smaller than predicted by DDH, in an explicit SU(6)-quark model analysis [1]. Our knowledge of H_π^1 was thrown into doubt by a measurement of nuclear spin-dependent PV effects in 6S-7S transitions in the ^{133}Cs atom [3] that has been used to extract a value for the cesium static nuclear anapole moment in the ground state [4]. Recently a full 2-body calculation of the cesium anapole moment has been used to place constraints on H_π^1 and the short-range, ΔI=0 rho-nucleon coupling, H_ρ^0 [5]. The cesium results imply a central value for H_π^1 two times larger than the DDH best value. To resolve the controversy between the ^{18}F and ^{133}Cs results and between different theoretical predictions, new high precision experiments such as the n+p$\rightarrow$d+ γ experiment [6] and a measurement of the rotation of neutron spin in helium [7] are needed. Since the n+p$\rightarrow$d+γ reaction involves a 2-body system, the result will give a strong constraint on the PV *NN* interaction that is free from nuclear theory uncertainties present in the interpretation of results from complex nuclei such as cesium or fluorine. The goal of the n+p→d+γ experiment is to measure the directional gamma-ray asymmetry with an uncertainty of $0.5\text{x}10^{-8}$ that unambiguously determines H_π^1 to ± 10% of its predicted value [1]. The experiment has been designed to keep systematic errors an order of magnitude smaller than statistical errors.

The n+p→d+γ experiment under construction at Los Alamos by the NPDGamma Collaboration is carefully designed for a pulsed cold neutron beam. Several components of the experiment are based on the use of time-of-flight (tof) to select the neutron energy. Also, tof information is used to control systematic errors *in situ*. An isometric picture of the apparatus is shown in figure 1. A detailed description of the experiment can be found in Ref. [6]. In the following we will discuss the n+p→d+γ experiment and its optimization on the SNS beamline 14B.

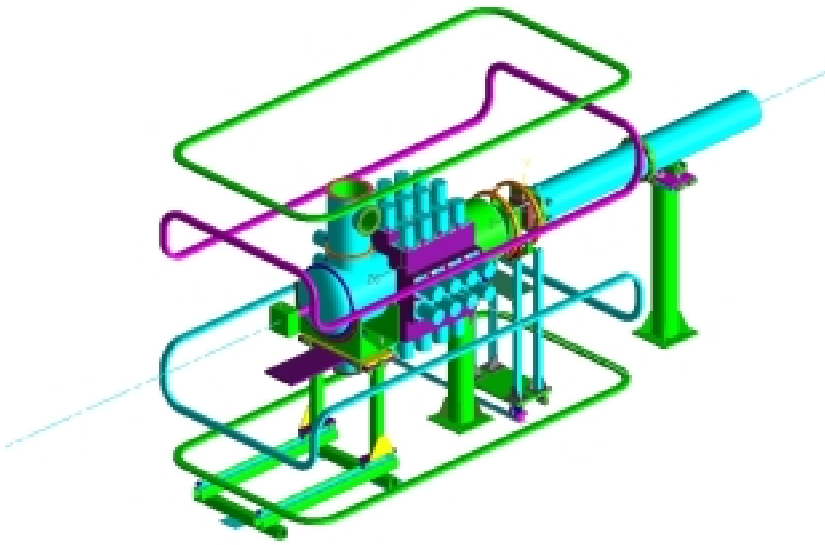

Fig. 1. Isometric picture of the n+p→d+ γ apparatus. The cold neutron beam from the SNS arrives from right. Shown are the last section of the vacuum tube containing the neutron guide and the beam monitor on the end of the guide. Next is the optically-polarized ^{3}He spin filter – 18-inch diameter NMR Helmholtz coils are shown - followed by the spin flipper, CsI γ-detector, and liquid hydrogen target. Behind the target is a ^{3}He beam polarization analyzer and a back beam monitor. Shown are also four race-track coils for a uniform 10-G magnetic guide field.

Neutrons from the SNS are guided to the experiment by a $10\text{x}12\ \text{cm}^2$ neutron guide. The guide includes a curved section that will prevent most of the fast neutrons and gamma rays from the source from reaching the target and detector. The neutron flux estimation assumes that the guide starts 1 m from the moderator surface and is 15 m long. The guide has a reflectivity of Θ_c=3.5 times that of ^{58}Ni. The calculated neutron flux per pulse as a function of tof at the end of the guide (at 16 m from the moderator surface) is shown in figure 2 [8]. The neutron flux is monitored by a thin ^{3}He ion chamber (M1) mounted on the end of the guide. After the monitor, the neutron beam passes through an optically-polarized ^{3}He spin filter [9]. The use of a ^{3}He polarizer is a key feature of the experiment; the acceptance angle of the ^{3}He spin filter is large and the capture of neutrons by ^{3}He does not create any γ-rays, which is an important feature for this γ-background-sensitive experiment. The ^{3}He spin filter is simple and compact. Also, the neutron beam polarization can be reversed without changing the direction of the guide field by an adiabatic fast passage of the ^{3}He spin. Behind the spin filter is mounted a second beam monitor (M2). M1 and M2 will be used to measure the beam polarization *via* transmission through the spin filter cell [9].

The main control of systematic errors and drifts is the neutron spin flip performed by an RF spin flipper (RFSF) that is able to flip the polarization of the neutron beam on a pulse by pulse basis [10]. The RFSF as well as the rest of the experiment works in a homogeneous magnetic field of 10 G. By changing the amplitude of the RF field synchronously with neutron tof, the RFSF will flip neutron spins at all energies with higher than 96% efficiency [10]. The neutrons are finally captured by a 20 liter para-hydrogen target located at 18 m from the source. The use of para-hydrogen is absolutely essential for two reasons: firstly, neutrons depolarize when scattering from ortho-hydrogen and secondly, the scattering cross section for ortho-hydrogen is so large that most of the neutrons would be scattered from the target before capturing if there was any ortho-hydrogen present. The 2.2-MeV γ-rays from the capture reaction are detected by an array of 48 CsI(Tl) crystals. Light from each of the crystals is converted to a current by highly linear and magnetic field insensitive vacuum photo diodes (with gain of unity). Current mode signal processing is used because the gamma rates are too high for counting. Low-noise and high-gain preamplifiers are used to amplify the currents from the vacuum photo diodes. The amplifier electrical noise will be two orders of magnitude or more smaller than counting statistics , a necessary condition for current mode detection.

The optimum frame frequency is 30 Hz as indicated in Table 1, where the integrated neutron flux per second is shown for different frame frequencies and integrated tof intervals.

Table 1.

Frame (Hz)	TOF interval (ms)	Neutrons ($x10^{10}$ n/s)
60	10 - 17	6
30	10 - 33	9
20	10 - 48	7

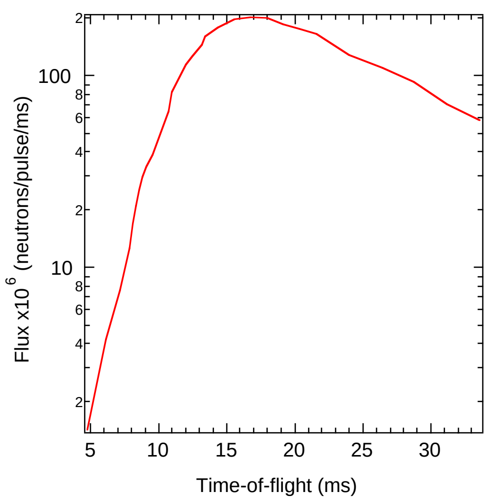

Fig. 2 Calculated neutron flux per pulse as a function of tof at the end of 16-m long beamline 14B at the SNS for a 30-Hz frame.

For captured neutrons with energy greater than 15 meV, depolarization will occur in liquid para-hydrogen by spin-flip scattering and therefore no parity violation can occur. Neutrons with energies less than 15 meV do not have enough energy to depolarize by flipping the proton spin and will therefore show a PV effect. This has led us to the following DAQ strategy per neutron pulse; from 0 ms to 10 ms after a proton pulse when the neutron energy is higher than 15 meV, the collected data is used to measure a null result. Then from 10 ms to 28 ms the collected data is used to determine the PV γ-asymmetry, and finally at 28 ms the frame definition chopper will shut off the beam and data is collected from 28 ms to the end of the 30-Hz frame to determine the beam-off background. Because of the very high neutron flux at the SNS, every A_γ will be measured with an uncertainty of about 10^{-5} in each neutron pulse.

The γ-yield is $6\text{x}10^9$ γ/s after accounting for neutron beam attenuation caused by the ^{3}He cell and other matter in the beam, the LH_2 capture efficiency, and the detector solid angle. This gives an estimation of 70 days run time on SNS beamline 14B to achieve the statistical error of $0.5\text{x}10^{-8}$. In addition to the statistical precision, systematic errors are a main concern of the experiment. We believe that the sources of false asymmetries are well understood and are safely below the limit of the statistical error. A discussion of systematic errors can be found in Ref. [6].

All the components of the Los Alamos $n+p\rightarrow d+\gamma$ experiment have been designed and most of them have been tested in beam. To answer several questions raised by reviewers we had a test run on the LANSCE cold pulsed neutron beamline, FP11A, with a 1/10th size version of the full $n+p\rightarrow d+\gamma$ experiment using ^{139}La and ^{39}Cl as targets. Parity-violating gamma asymmetries were measured from the targets with uncertainties of 10^{-6} [11]. When scaled to the expected detector solid angle, neutron polarization, and beam intensity, the test experiment has demonstrated that the $n+p\rightarrow d+\gamma$ experiment at the SNS can reach its uncertainty goal of $0.5\text{x}10^{-8}$ in the estimated run time.

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